UCRL- 93888
PREPRINT

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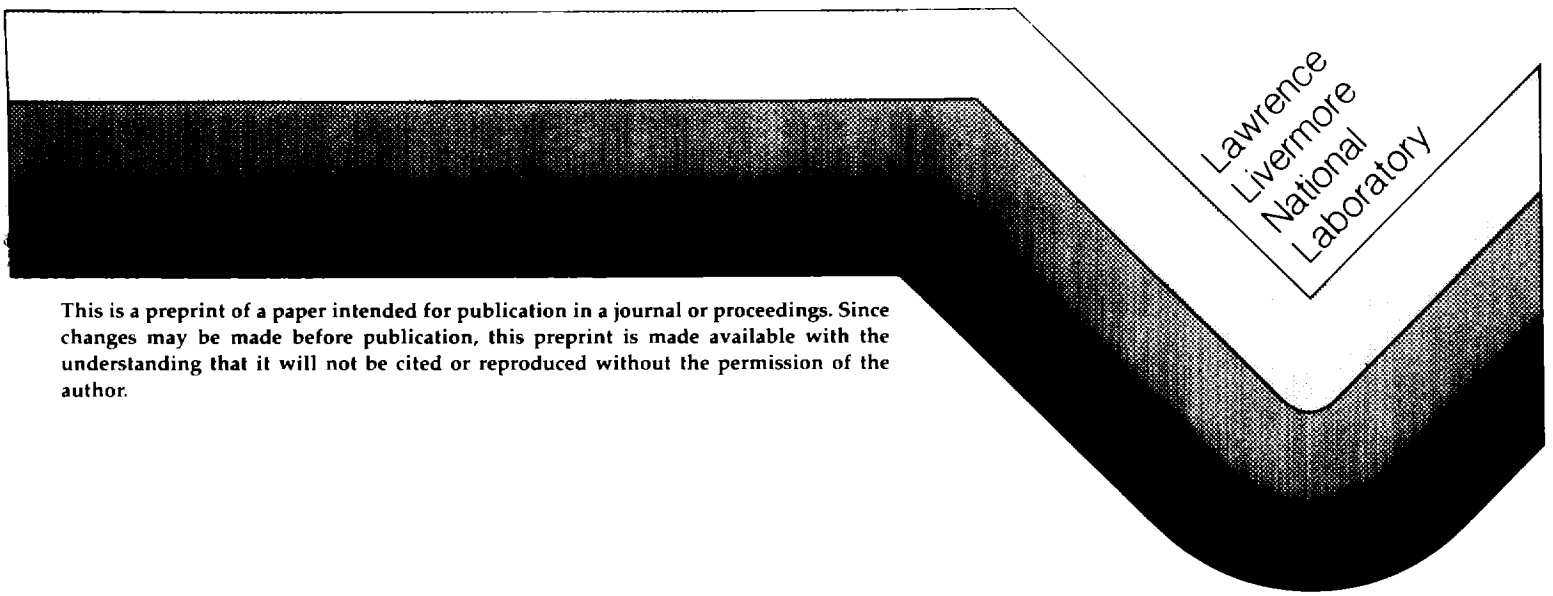
This paper was prepared for presentation at the Canadian and Western States Section of the Combustion Institute, 1986 Spring Meeting, Banff, Alberta, Canada, April 28-30, 1986



Development of a Reliable Method for In Situ Ignition of Coal Through a Lined Borehole

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ABSTRACT

Reliable permeability enhancement of a coal seam necessary for successful underground coal gasification (UCG), can be achieved by drilling a horizontal borehole low in the seam connecting gas injection and production wells. Economic considerations dictate that the number of burn modules per horizontally drilled hole be maximized and gas quality remain relatively constant. For these reasons the controlled retracting injection point (CRIP) method was developed by Lawrence Livermore National Laboratory. The CRIP method involves the insertion of a small-diameter retractable igniter tube terminated by a burner/nozzle assembly into the deviated borehole. A gaseous fuel is introduced in this tube to burn in an outer oxidant flow at the nozzle and ignite the coal at this point. As the UCG cavity develops to encompass inert overburden and the quality of the produced gas begins to drop, the small tube is retracted to a new point upstream and the coal ignited here to start a new UCG module. In this way a number of modules can be gasified from the same borehole, and the produced gas quality can be maintained for relatively long periods of time.

For structural and flow conductance reasons the horizontal borehole must be lined with steel pipe, which the CRIP igniter must be able to burn through. Other considerations crucial to the successful CRIP operation are the method used for the remote ignition of the gaseous

This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under contract No. W-7405-Eng-48.

reactants, the time required to burn through the pipe as a function of ambient and flow conditions, and the degree of backburning of the steel pipe during the procedure. This paper summarizes previous field and laboratory development of the CRIP system, and describes recent efforts which tested burner designs and breakaway burner heads for in situ backup use, and measured burnthrough times for stainless steel pipes for a variety of gas flow rates and compositions. Factors controlling the success of a liner burnthrough were identified to be the oxygen content in the oxidant gas, and the heat loss characteristics of the medium surrounding the liner. The burnthrough time for successful experiments was not entirely reproducible, but was shown to be influenced by the convective heat transfer rate from the combustion gases to the tube wall.

INTRODUCTION

Underground coal gasification (UCG) presents a promising alternative to conventional mining for recovering the energy of coal in place. In UCG, coal is partially combusted and then gasified in situ by injected air and/or oxygen/steam, creating a product gas consisting of varying amounts of hydrogen, carbon monoxide and methane, suitable for upgrading into a variety of products. To successfully gasify a coal seam in situ, a permeable link must first be estabilished between drilled gas injection and production wells. This prevents high pressure drops from occuring through the seam and ensures economically high gas production rates. In recent years, directional drilling techniques have become the favored method for creating permeability enhancement in the coal seam. These techniques, although potentially more expensive than others such as reverse combustion and hydrofraccing, are more reliable and can place the link low in the coal seam for optimum recovery.

The life a a UCG burn is limited since the cavity developed eventually grows to encounter inert overburden material. This introduces excess water into the burn zone and itself acts as a heat sink to reduce produced gas quality to unacceptable levels. Therefore, UCG modules must be periodically moved to new locations in the seam. Also, economic considerations dictate that the number of UCG modules per deviated drilled well be maximized. The controlled retracting injection point (CRIP) method developed by Lawrence Livermore National Laboratory (Hill and Shannon, 1981) meets these objectives. In the CRIP procedure, a retractable tube terminated with a burner/nozzle assembly is placed in the deviated injection borehole which is intersected downstream by a gas production borehole. Fuel flowing out of this tube into the outer annular flow containing oxygen is ignited at the burner. This flame in turn ignites the coal and initiates a UCG module at this location. The tube is retracted upstream, and when the active UCG module has reached the end of its lifetime in terms of good gas production, the coal is ignited upstream at the burner by the same procedure. A conception of this process is shown in Figure 1. In this way a number of UCG modules can utilize the same drilled link, and a relatively constant gas quality can be maintained for a long period of time. For CRIP to be successful, reliable remote ignition of the fuel at the end of the tube must be ensured. Also, the igniter must be able to burn through the liner material in the borehole in a reasonably short time.

The first application of the CRIP process in a series of small-scale UCG tests (Thorsness and Hill, 1982), employed pyrophoric silane gas (SiH_4), which ignited upon contact with oxygen in the outer flow, to ignite methane which followed the silane out of the small tube. During these tests ignition failed to occur in some instances, and therefore a laboratory study was undertaken to study the

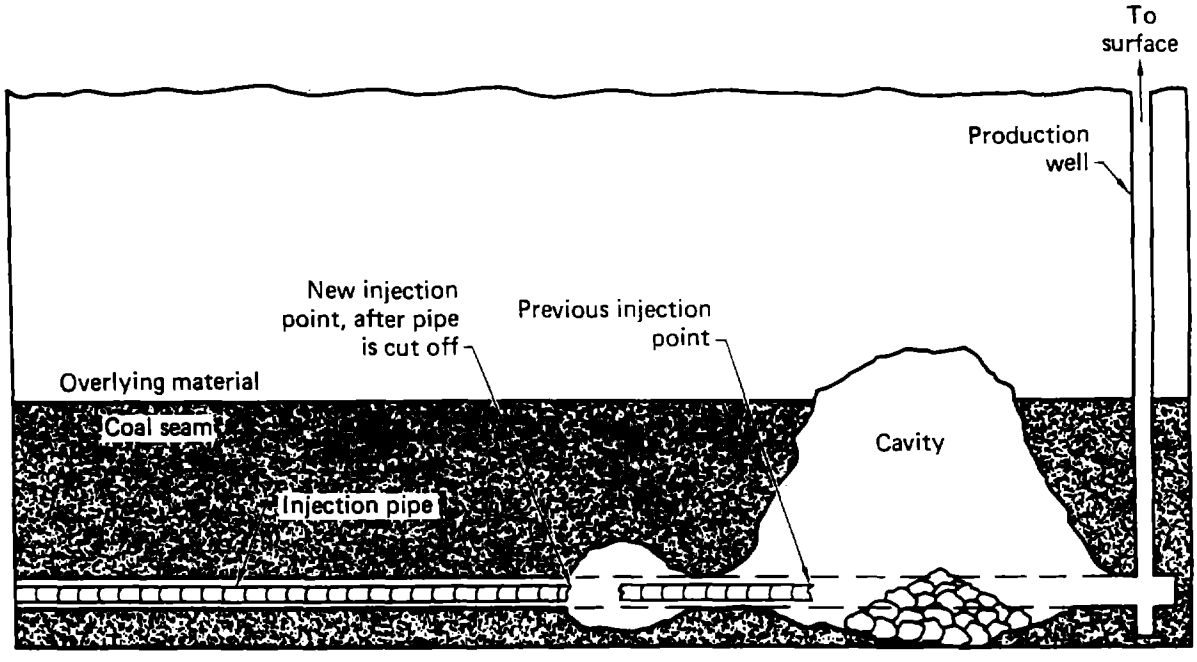

Figure 1. Basic design of the controlled retracting injection point (CRIP) system. As the UCG cavity burns toward the left, the injection point is moved to the left also, step by step, by cutting the injection pipe remotely from the surface. Thus the injectant gas is always being fed to a zone of the coal seam where unburned coal remains to be gasified.

characteristics of the silane-fuel-oxygen system (Thorsness et. al., 1982). Results of this study showed that ignition of the fuel by the silane always occurred for low to moderate pressures if a slug of silane were introduced into the small tube, the flow stopped in this tube and then slowly restarted by introduction of the fuel. This procedure apparently prevented blowoff of the silane flame upon ignition. These studies discovered an upper pressure limit of about 16 bar (230 psia) beyond which silane failed to ignite at all, Also, it was determined that under pressures for which it remained in the gas phase, propane created a more stable flame than methane and was therefore preferred for pressures up to about 5 bar (70 psia).

Following these tests, the CRIP system was tested in a large UCG demonstration at a coal mine near Centralia, Washington (Hill et. al., 1984). The CRIP system was successful in initially igniting the coal and for igniting a second module later in the test after retraction. The burner became stuck at this second CRIP point however, probably due to fusion with the liner. This event raises concerns difficult to address in the field due to the remoteness of the ignition zone; namely, uncertainty as to the time required for adequate burnthrough of the pipe under downhole conditions, and to the likelihood of burning or melting of the liner back to the nozzle to cause sticking and render the burner useless.

The CRIP method as described above is designed to cut through the liner and ignite the coal at several discrete points. However, sealing of the borehole around the liner caused by coal creep at the very high lithostatic pressures present in deep coal seams could, conceivably require a more extensive destruction of the liner for sufficient coal-oxygen contact. Also, wellhead sealing problems and mechanical problems associated with a retractible fuel injection tube in a short-radius deviated borehole may make this type of CRIP

operation unfeasible under such conditions. For these reasons a planned UCG experiment in Belgium, carried out by a joint Belgian-West German development agency, will attempt to utilize the CRIP method to ignite and continuously back burn a carbon steel liner so as to completely destroy it during the gasification process. In support of this project, a series of laboratory experiments were performed to study the backburning rate of carbon steel pipes under simulated UCG conditions. These tests explored the effects of the pipe size and wall thickness, pressure, oxidant and fuel flowrates (Depouhon et. al., 1985). The experiments showed that there is a minmum oxygen concentration of about 70% in the oxidant flow below which sustained backburning of the carbon steel liner, after ignition by a silane-methane-oxygen flame, does not occur. They also suggest that the burning velocity of the steel is independent of the oxygen partial pressure but increases with the oxygen flow. Also, experiments with flexible liners consisting of pipe sections connected with flexible joints demonstrated the difficulty of sustaining liner combustion across the joints, probably due to the decreased thermal conductivity of the liner at these points.

The previous discussion has described the state of the art in igniting coal through steel liners in situ, and pointed out the progress made and the questions that remain. The remainder of the paper describes recent work done to ensure the destruction of stainless steel liner by in situ combustion, and to determine burnthrough times for this material as functions of oxygen and fuel flow rates and compositions.

EXPERIMENTAL

Type 304 stainless steel tubing, OD=10.16 cm (4 in.), ID=9.83 cm (3.87 in.), cut into sections approximately 2 m long served as the liner material to be cut in the

experiments. Oxidant was supplied through a 3.24 cm (3/4 in.) stainless steel tube terminated at an aluminum press fitting placed in one end of the liner. A fuel supply tube of the same type terminated by a burner head continued through the press fitting to end about 102 cm (40 in.) downstream in the liner. This setup is shown in Figure 2. Oxygen and propane were supplied by cylinders, and air was obtained from the house supply, or from a manifold of cylinders for the high-air flow experiments. A 6.5 % silane in argon (Matheson) bottle, plumbed into the fuel supply tube, provided the remote ignition method. The silane/fuel supply lines contained numerous check valves to prevent unintentional release of silane, and utilized a small reservior bottle to store and deliver a controlled volume of silane to the fuel line. A nitrogen bottle was also plumbed into the fuel/silane supply to purge the lines prior to a run. Propane flowrates were manually set, while oxygen and air flows were monitored by a data aquisition system based on a Hewlett Packard A1000 minicomputer.

Liners to be cut were surrounded on all sides by a layer of firebricks. A gap of about two centimeters was left to allow visual inspection during the experiment. A 4.1 cm (1-5/8 in.) hole was cut through one firebrick, and this placed at the expected burnthrough position of the liner sidewall. The sidewall temperature at this position was measured and recorded by an optical pyrometer, which sent voltage outputs to a strip chart recorder and to the computer. The firebricks were replaced between runs to maintain a constant initial environment.

Essential to a safe and reliable ignition in the liner was the following ignition procedure (Thorsness et. al., 1982). First, the fuel lines were purged with nitrogen. A small silane charge, slightly more than one line volume, was prepared in the reservoir bottle. A preset air flow was initiated in the annular region of the liner. The silane

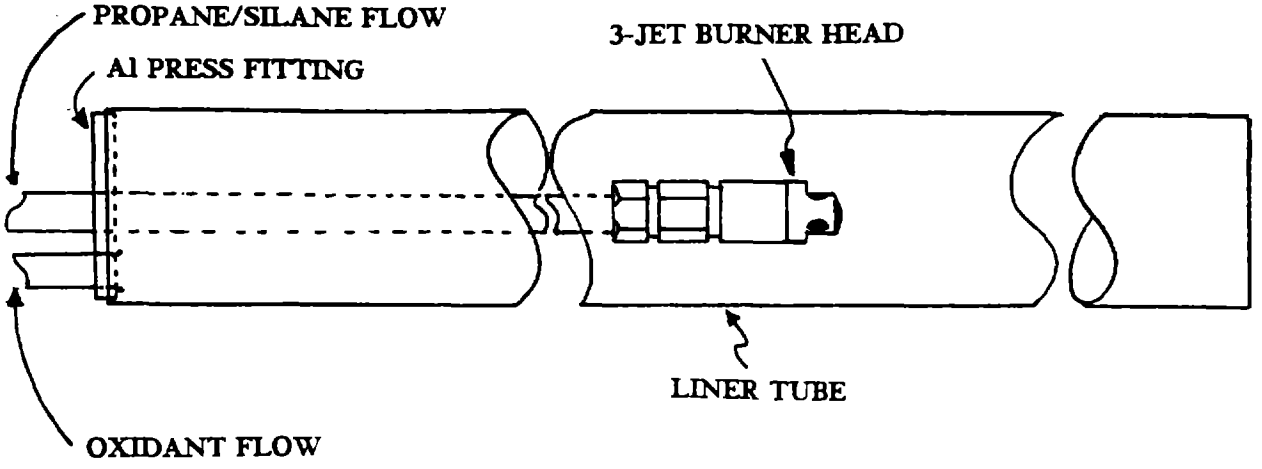

Figure 2. Schematic of the pipe burning apparatus.

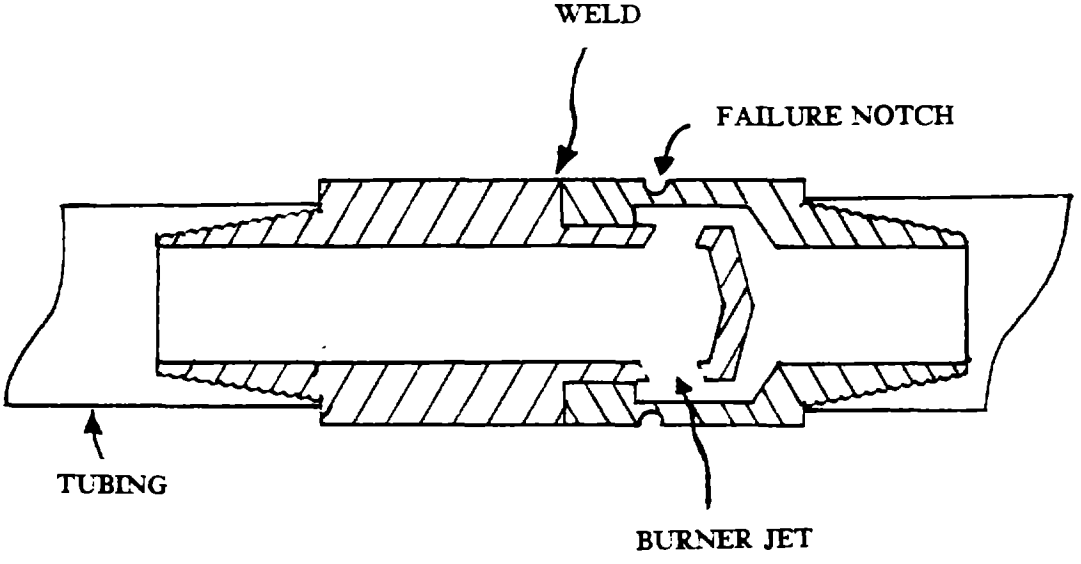

Figure 3. Design of a breakaway nozzle for backup purposes in situ.

charge was then introduced into the fuel tube, and then the flow in this tube stopped. An ignition occured at this time, evidenced by a pop and by smoke issuing from the end of the pipe. A small propane flow was then started in the fuel tube, and after a few seconds, the propane flow was increased to its prescribed value. At this point the oxygen flow was immediately turned on to its preset value. Using this procedure, sucessful ignitions were attained in 100% of the experiments.

RESULTS

Preliminary experiments were performed to test burner head design and to test the performance of a breakaway burner designed as an in situ backup in case the primary burner head became stuck downhole after a CRIP maneuver. In regard to the former, 3-jet and 4-jet burner heads were manufactured and tested. Both designs were successful in destroying the liner, but the 3-jet burner was deemed the more satisfactory since it appeared that lower flows could be used to achieve similar burnthrough times with this design. The first design of a breakaway burner consisted simply of an open tube formed by failure of a deliberately weakened coupling in the fuel line. Burnthrough of the liner was not achieved with this design, probably because a jetting action concentrating the heat release on a small section of the liner wall is necessary for melting. Therefore a breakaway nozzle assembly was designed and successfully used to destroy the pipe. This design is shown in Figure 3. It consists of sleeve which slips over and is welded to the base of a 3-jet burner head. This sleeve is notched downstream of the weld such that it fails at a force in tension of 15-25 kN (3.4-5.6 klbs).

A later series of experiments were then undertaken to quantify burnthrough times for a variety of flow conditions, and to determine a minimum oxygen concentration required to

achieve burnthrough under laboratory conditions. For these experiments, burnthrough times were defined to be the elapsed time between the onset of full oxidant flow and a major collapse event of the upper part of the liner. The term "burnthrough" is used here rather loosely, since examination of the liners after the experiment showed that they generally melted rather than burned, although in some instances small oxidation holes appeared a few centimeters upstream of the melted region. A summary of conditions and burnthrough times for these experiments is given in Table 1. Most of the experiments were carried out under stoichiometric or fuel lean conditions, since these are of more interest in the field.

During the course of the experiment, the tube wall temperature would rapidly rise and then level off to a constant or very slowly varying function of time, depending on flow and exterior conditions. This behavior is demonstrated in Figure 4, which shows sidewall temperature profiles as functions of time for experiments 2 through 6. (Such temperature data were not taken for the later experiments due to failure of the pyrometer). If the heat transfer rate from the gas to the pipe wall remained larger than the heat loss rate to the firebricks, the melting temperature of the steel (approximately 1300 C) would be eventually exceeded on a small region of the sidewall opposite and somewhat downstream of the jets, and small bubbles would appear here, and grow. When the bubbles coalesced at the top of the liner, collapse was imminent. A representative liner after a successful burnthrough is shown in Figure 5.

Reproducible burnthrough times under identical flow conditions were not demonstrated in early experiments. For example, failure times for the (nominal) base case of 40 mmol/s propane, 200 mmol/s oxygen and no air flow ranged from 121 s to 242 s, with an average failure time based on 7

TABLE 1
SUMMARY OF PIPE BURNING EXPERIMENTS

EXP. #	----FLOWS (MMOL/S)---- PROPANE	OXYGEN	AIR	% O IN FEED	EQUIV. RATIO[a]	BURNTHROUGH TIME (S)[b]
1	40	210	0	100	0.95	157
2	40	245	0	100	0.82	209
3	40	275	0	100	0.73	214
4	40	190	0	100	1.05	150
5	30	140	0	100	0.93	304
6	30	150	0	100	1.00	347
7	40	202	0	100	0.99	121
8	40	200	0	100	1.00	---[c]
9	40	200	0	100	1.00	173
10	40	204	0	100	0.98	242
11	40	230	50	86	0.83	269
12	40	232	50	86	0.83	205
13	40	202	0	100	0.99	199
14	40	200	0	100	1.00	218
15	40	200	0	100	1.00	---[d]
16	40	203	50	84	0.94	250
17[e]	40	198	50	84	0.96	365
18[e]	40	205	50	85	0.93	330
19[e]	40	205	100	74	0.89	433
20[e]	40	204	100	74	0.88	400
21[e]	40	205	150	67	0.85	398
22[e]	40	198	200	60	0.83	462
23[e]	40	164	200	56	0.97	593
24	40	205	0	100	0.98	---[f]
25	40	0	661	21	1.44	---[g]
26	40	83	508	32	1.05	---[g]
27	40	124	387	40	0.97	---[g]

[a]defined as 5*fuel/oxygen
[b]measured from onset of oxidant flow
[c]no burnthrough after 300 s
[d]run aborted after explosive spall of insulation layer
[e]moisture in firebricks increased burnthrough times
[f]no burnthrough when firebricks removed and pipe exposed to open environment
[g]no burnthrough

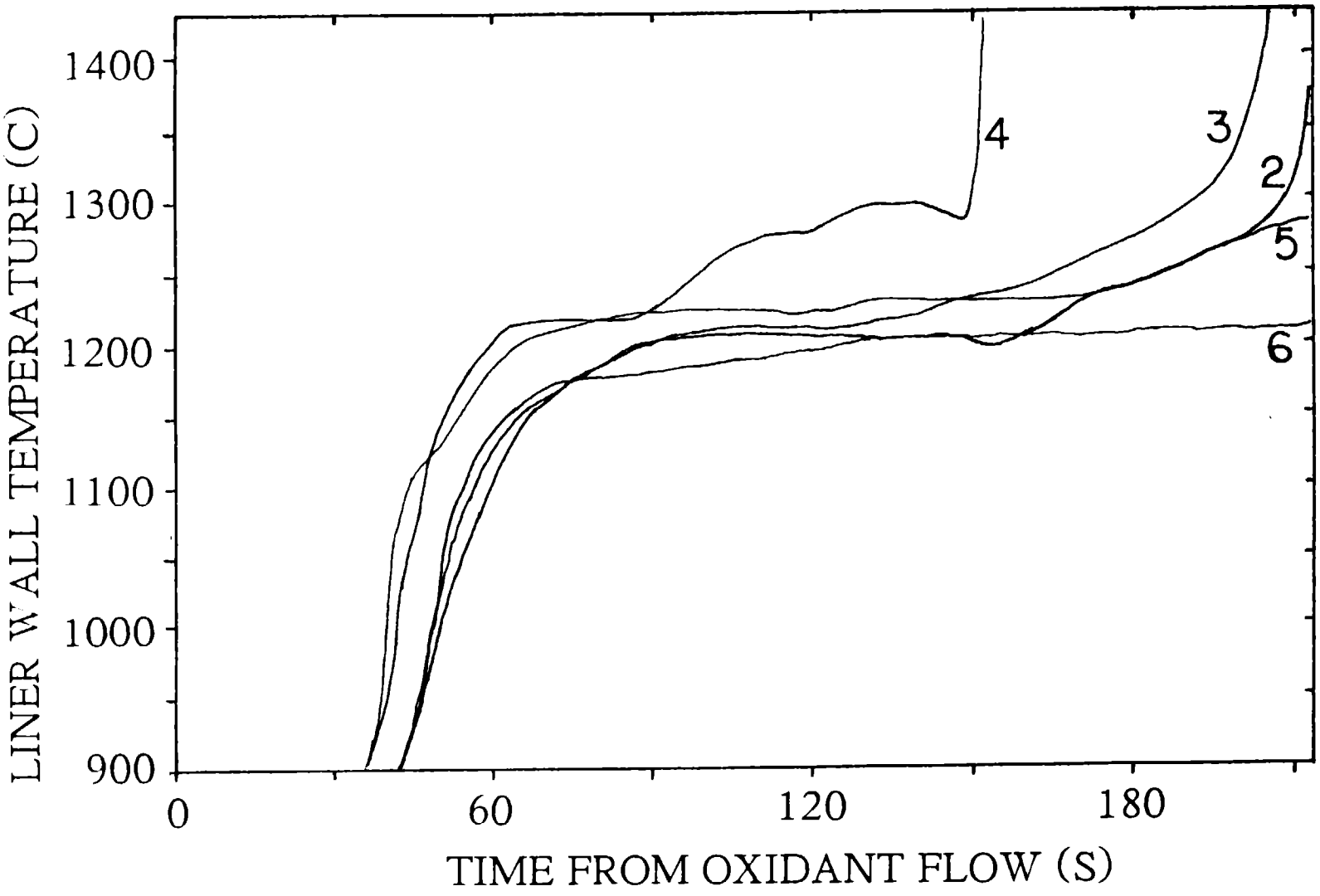

Figure 4. Sidewall temperature profiles for experiments 2-6. Rapid temperature rise at right for experiments 2-4 indicative of burnthrough.

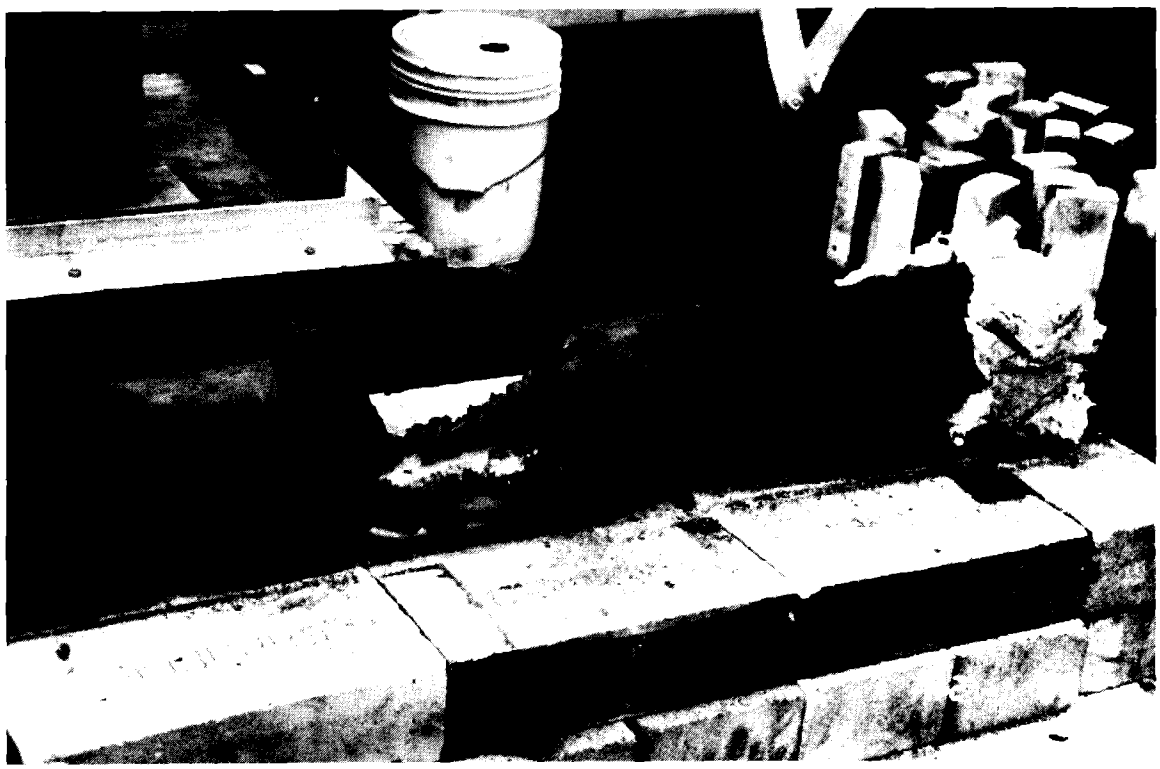

Figure 5. Rperesentative liner after burnthrough.

experiments of 180 s. This does not include one test (#8) in which major collapse of the liner did not occur within 300 s, after which the run was ended. This sample did exhibit a sizable hole on one side and a number of smaller holes throughout over the affected area, however. As a result of this scatter, later experiments concentrated on the occurence of burnthrough as a function of air dilution. These experiments used propane flowrates of 40 mmol/s and oxygen concentrations ranging from 21 to 100%. Burnthrough was achieved for a stiochiometric oxidant flow consisting of 56% oxygen, and for all experiments which used oxygen contents greater than this. An attempt with a stoichiometric oxidant flow of 40% oxygen, and all attempts with oxygen contents below this value, failed to burnthrough after 15 minutes of operation, a time long enough to assure steady heat loss rates in this system. The influence of exterior boundary conditions on the burnthrough behavior was also demonstrated by one experiment (#24) in which the firebricks on the sides and top of the tube were removed, exposing the liner to the open environment. The greatly increased heat loss rate prevented burnthrough.

DISCUSSION

Variability of burnthrough times for constant flow conditions was largely due to the stochastic nature of bubble growth and coalecesence on the upper half of the tube. The burner was oriented such that one jet aimed down, and the other two at 60 degree angles along the sidewall. Bubbles which formed on the sidewall needed to grow and meet at the top of the tube for a major collapse event to occur. In a number of cases, smaller holes were formed on the sidewall some time before the collapse. These could have served to alter the heat transfer to remaining intact portions of the tube wall in a manner that was irreproducible.

Lack of burnthrough in the experiments which used high rates of air dilution is felt to be due to a lowering of the combustion gas temperature below that needed to overcome heat losses at the melting temperature of the sidewall, and not due to a decrease in the oxidation rate of the liner. This is because, as mentioned earlier, the stainless steel liners appeared to fail more due to melting than to oxidation.

Sidewall temperature profiles for the earlier experiments (see Figure 4) generally show a rapid increase in the wall temperature followed by a longer period during which the temperature rises slowly as the heat transfer rate to the firebricks gradually declines as they become hot. This suggests that a rudimentary analysis of the heat transfer at the pipe wall may be useful in interpreting the data for the tests in which liner destruction was successful. For simplicity we consider as an analog to the experimental system a one-dimensional semi-infinite slab internally at ambient temperature, with a slowly varying surface temperature, to leading order constant, applied at time zero. Heat is being supplied to this surface by a hot flowing gas. At any instant of time the heat flux at the surface is given by the balance between convective and conductive heat transfer:

$$h(T_g - T_w) = -k \frac{\partial T_w}{\partial r} \Big|_R \qquad (1)$$

where h is the convective heat transfer coefficient to the wall, T_g is the combustion gas temperature, T_w is the wall temperature which is a slowly varying function of time, k is the thermal conductivity of the solid, and the length coordinate is scaled with the the tube radius, R. The temperature profile in the medium is given by the classical similarity solution to unsteady heat flow in the slab (Carslaw and Jaeger, 1959), which shows that the temperature

gradient at the surface is proportional to the square root of time:

$$\frac{\partial T_w}{\partial r}\Big|_R = \frac{CR}{\sqrt{\alpha t}} \qquad (2)$$

where α is the thermal diffusivity of the medium, taken to be 1.6×10^{-3} cm^2/s for the firebrick, and C is a constant proportional to the difference between T_w and the ambient temperature T_a. Inspection of the above equations suggests that the burnthrough occurs when $T_w = T_m$, the melting temperature of the steel. If we assume that h is equal to a constant multiplied by a power ν of the Reynolds number Re which varies from experiment to experiment, this formulation suggests that a plot of:

$$\frac{\sqrt{\alpha t_b}}{R} \text{ -vs- } \frac{T_m - T_a}{Re^{\nu}(T_g - T_m)} \qquad (3)$$

can provide a linear relation between burnthrough times and other system parameters. A measure of the gas temperature T_g in Eq. 3 is given by:

$$T_g = \frac{Q_{rxn}}{\Sigma_i F_{pi} C_{pi}} \qquad (4)$$

where the heat of reaction Q_{rxn} assumes complete combustion of the propane at the melting temperature according to the stoichiometric formula:

$$C_3H_8 + 5O_2 \rightarrow 3CO_2 + 4H_2O \qquad (5)$$

and the thermal capacity is taken to be that of the sum of product gas flowrates F_{pi} multiplied by their heat capacities C_{pi} evaluated at the melting temperature.

A plot of the data of Table 1 according to the above derivation is shown in Figure 6, assuming $\nu = 0.5$. Although the data is somewhat scattered, there is a definite trend

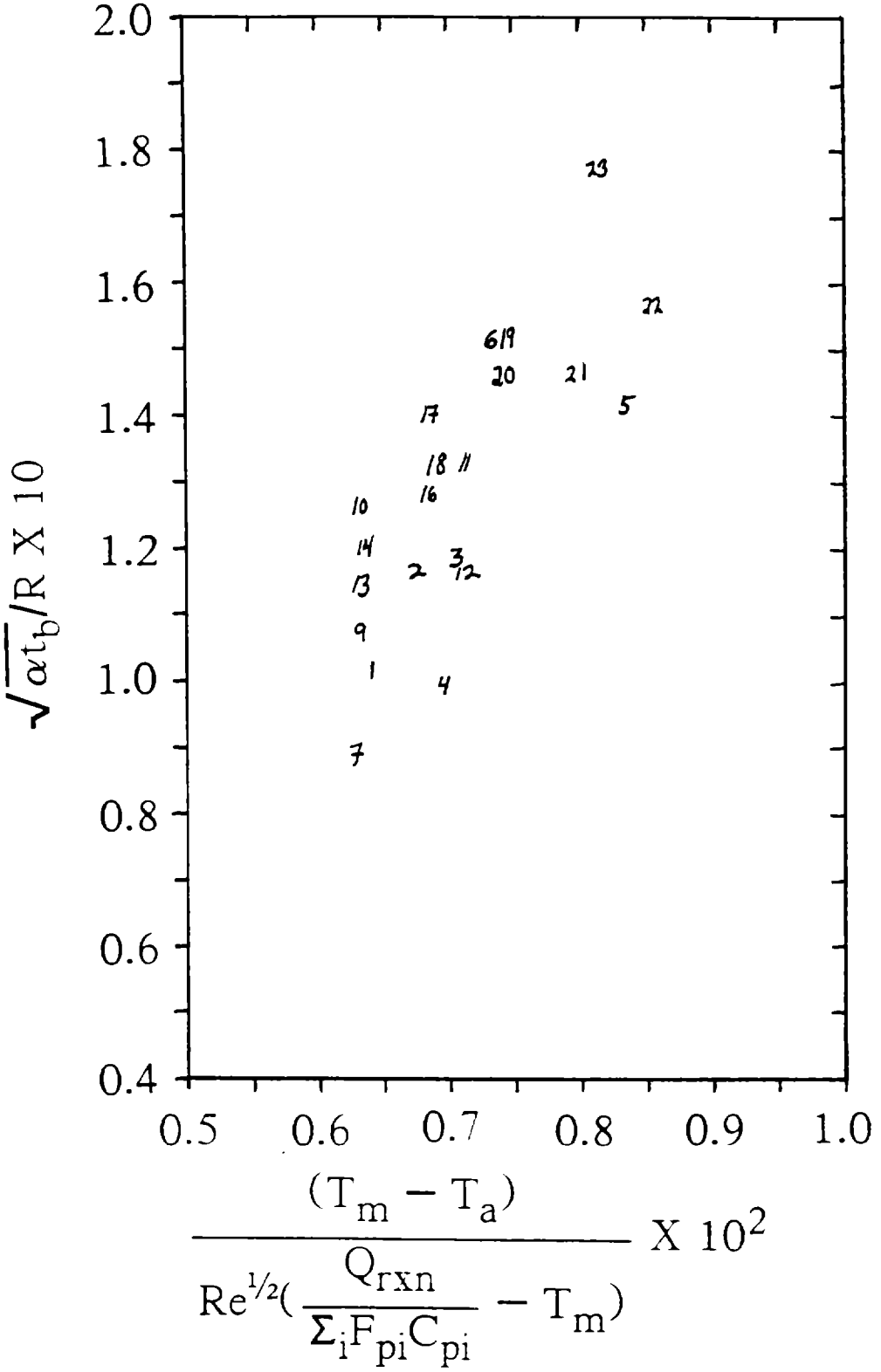

Figure 6. Dimensionless burnthrough time plotted against dimensionless heat transfer rate inside tube, according to Eq. (3).

that shows the burning time to vary inversely with the heat transfer rate from the combustion gas to the tube wall. Linear regression of the data shown on Figure 6 gives the following relationship between the groups defining the x and y axes:

$$y = 24.2\ x - 0.042 \qquad (6)$$

The burnthrough time is seen to be a strong function of the heat transfer rate in the tube. This analysis is complicated by the fact that the Reynolds numbers based on the product gas flow ranged from 1500-10000 for these experiments, a transition range in which the dependence of the heat transfer on Re is variable. According to standard correlations, the heat transfer coefficient is proportional to $Re^{1/3}$ at the low flows and to $Re^{0.8}$ for the higher flows, and thus the entire set of experiments cannot be represented by a constant value of ν. The importance of this effect was demonstrated by plots made of the above data for ν=0.33 and ν=0.8, for which low-flow data points lie to the right and left side of the mean, respectively. This analysis cannot address the lack of burnthrough for the high air dilution experiments, other than to estimate conditions in which lowering of the gas temperature by nitrogen dilution or a decrease in the heat transfer coefficient causes insufficient heat transfer to occur with the surface at T_m. It is at this state that liner destruction is not possible. Burnthrough did not occur for values of the group defining the axis of Figure 6 greater than about 0.01.

Available data indicate that the thermal diffusivity of wet coal at ambient conditions is about one-half that of the firebrick used in this study, although the porosity increase upon drying and pyrolysis of subbituminous coal causes the thermal diffusivity to be a strong, increasing function of temperature. However, the higher pressures during a burn in

situ will concentrate the heat release zone over a smaller region of the liner surface, and higher fuel and oxidant flowrates will be possible. Thus, for the same flows it is felt that in situ burnthrough times will be comparable or somewhat faster than those of this study, provided that freely flowing water is not present in the annular region between the liner and the coal. The possible presence of such water is unpredictable and can have a dramatic impact on the liner destruction characteristics.

CONCLUSIONS

A series of experiments in which stainless steel tubing was destroyed by a remote internal propane flame have been performed in support of the underground coal gasification program at Lawrence Livermore National Laboratory. The experiments successfully tested a breakaway nozzle assembly and delineated a range of fuel and oxidant flows for which destruction of the liner is possible. Burnthrough of the liner was demonstrated at propane flows as low as 30 mmol/s stoichiometric and lean conditions. It was found that for propane flowrates of 40 mmol/s, stoichiometric oxidant flows containing at least 55% oxygen are required for burnthrough under laboratory conditions. Data on burnthrough times was scattered, but an analysis suggests that the time required for burnthrough depends inversely on the square of the heat transfer rate from the combustion gases to the tube wall, and inversely on the thermal diffusivity of the surrounding medium.

Acknowledgements

The authors are indebted to Doug Fields and Dan Nelson for invaluable assistance during the experiments.

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